Photovoltaic Orientation & Power Output

Student Objective
The student:
- can predict how a photovoltaic module's tilt angle in relation to the Sun will affect its power output
- can predict how the solar azimuth will affect the power output of a photovoltaic module
- can explain how the angle of solar incidence is used to calculate the optimum array tilt angle
- can determine the best angle for a fixed panel to maximize its power for various times during the average year
- can determine how to face a photovoltaic array to maximize its output to match the utilities' peak load time
- will use voltage, current, and power data to provide explanations.

Key Words:
array tilt angle
azimuth
insolation
irradiance
irradiation
latitude
Ohm's Law
peak sun hours
solar incidence

Time:
1 - 2 class periods

Materials:
- Laboratory Manual
- photovoltaic module
- irradiance meter (solar meter)
- multipurpose meter
- wires with alligator clips
- protractor
- ruler
- rod or other long thin object
- graph paper
- compass
- heavy paper or cardstock

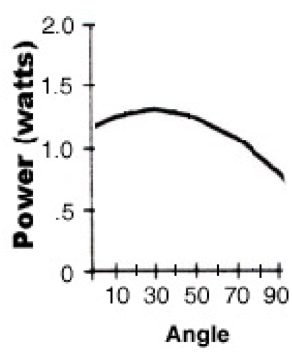
Procedure
1. **Engage:** Lead a discussion on the questions and results from the *PV Power Output and I-V Curve* exploration and answer any questions that the students have from the problem

set. Most of the general PV questions that the students have, would make good independent (internet) research. Extra credit could be given to students who research a class question and report the answer.

2. Points that may be brought up in discussion that will be covered more thoroughly during this investigation, and thus could be given a "you will find out today" response:
   - Modules were very sensitive to what direction they were pointing in relation to the Sun, thus causing differences in the data collected.
   - The time of day would affect the data collected.
   - Student readings were lower than manufacturer's specifications; some reasons for this will be discovered today.
3. Review any terms that are confusing to the students: solar noon, short circuit current, open circuit voltage, maximum power point, etc.
4. Students should work in teams of 3 - 5 per team. Pass out materials.
5. **Explore:** Students should follow written procedures and complete the activities in the Laboratory Manual.
6. The problem set is optional. It synthesizes and evaluates student knowledge.

Answers - Laboratory Exercises

1. Varies depending on class time. However, there should be consistency between groups.
2. The data will vary depending on the irradiance level during class time. However, the average power outputs should be fairly consistent between groups.
3. The graphs will vary from class to class, however a typical example is below. Graphs should be labeled with units and titled correctly. The independent or x- axis is tilt angle, dependent or y-axis is power (watts) and graph intervals should be equally spaced. The title of the graph should include the irradiance level when the readings were taken.



4. Answers will vary, but students should indicate that the angle of incidence of the PV system has a direct relationship to the output of voltage, current, and power.

5 - 8. Students should conclude that the maximum power, voltage and current output is obtained when the face of the panel is perpendicular (90º) to the angle of solar incidence. Formulas should reflect this:

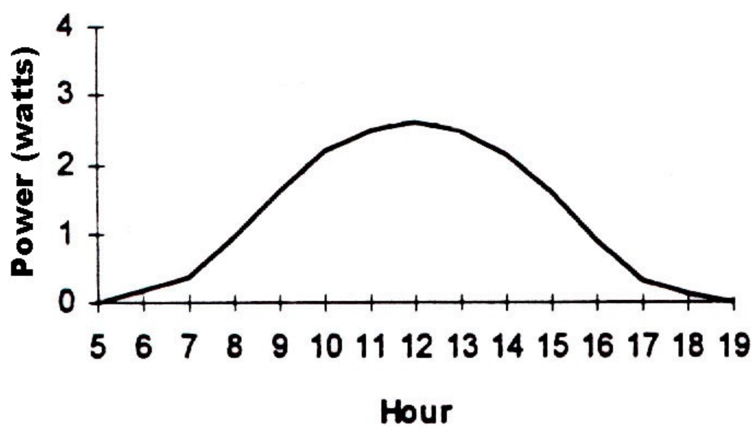
$\beta = 90 - \alpha$ or

$\beta = 180 - (90 + \alpha)$

8. Answers will vary, but should include the concept of the changing Sun path depending on

the time of day, latitude of the location and the season of the year; therefore constantly changing the optimum array tilt angle.

9. Varies depending on class time, but should be consistent between groups.
10. 15º per hour (360º / 24 hours or 180º / 12 hours)
11. The data will vary depending on irradiance level during class. However, the average power outputs should be fairly consistent between groups and students should recognize a pattern of decreasing power as time changes before and after solar noon.
12. Students should indicate that the simulated azimuth angle has a direct relationship to the power output of the module.
13. The graphs will vary from class to class, however a typical example is below. Graphs should be labeled and titled correctly. The x-axis (independent variable) is simulated time, y-axis (dependent variable) is power, and graph intervals should be even. The title of the graph should include the irradiance level, and the word "simulated" should appear in the title.



14. Solar Noon
15. Answers may vary, but should include the range of times around solar noon (i.e. 10:00 - 2:00 or 9:00 - 3:00)
16. Students should indicate the range of times that represent the upper 50% of their graph. 10:00 - 2:00 or 9:30 - 2:30 is typical.
17. Answers will vary, but students should understand that maximum power is produced when the angle of incidence of sunlight to the face of the module is 90º.
18. Students should indicate that the array will be positioned to face in a more westerly direction. Some students may realize that to position the array for a 5:00 peak load would require positioning the array 65º to the west of solar noon.
19. Students should realize that as the position of the Sun gets closer to the horizon the amount of atmosphere it needs to travel through increases. The increased atmosphere decreases the amount of power because it diffuses more of the sunlight.
20. More energy
21 Answers may vary, but students should understand that an increase in cost would be associated with including a tracker in the system, and that the tracker would also require energy to operate, thus affecting the net power output.

22. 4.69 kWh/m^2
23. 6.27 kWh/m^2; May; 0° tilt angle
24. December, 40°
25 Approximately the same. Answers will vary, but students should realize that the table data is an average of the particular years, therefore mitigating circumstances like unusual weather could contribute to a slight difference from year to year.

Answers - Problem Set

1. 15
2. -67°
3. Orlando 4.69; Tonopah 5.82; Spokane 3.86
4. Orlando – 4.95, 25°
   Tonopah – 6.55, 30° and 35°
   Spokane – 4.40, 35°
5. Orlando – May, 6.27, 0°
   Tonopah – June, 8.80, 0°
   Spokane – July, 7.44, 0°
6. Orlando – December, 40°
   Tonopah – January, 50°
   Spokane – December, 60°
7. No, no, no
8. Answers will vary, but students should realize that the weather in each city directly affects the solar insolation received.
9. (a) When a PV array is tilted at a lower angle than latitude, the energy production will typically peak during the summer months.
   (a) PV arrays tilted at angles higher than latitude will generally have higher energy production during winter months.
10. East orientated PV arrays will produce more energy in the morning hours, and west orientated PV arrays will produce more energy in the afternoon hours. Students may also state that west-facing arrays may be beneficial for producing more energy during the utilites' peak load hours.

Key Words and Definitions

- **array tilt angle** – the angle made between the Earth's surface (horizontal) and the PV array
- **azimuth** – the horizontal angular measure between due south in the Northern Hemisphere and the point on the horizon directly below the Sun
- **insolation** – the amount of solar energy received on a surface expressed in units of kilowatt-hours per square meter. Insolation is essentially the average solar irradiance integrated with respect to time.
- **irradiance** – the measure of the power density of sunlight. Expressed in watts per square meter. The solar constant for earth is the irradiance received by the Earth from the Sun, 1367 m^2, at the top of the atmosphere and $\approx$1000 W/m^2 after passing perpendicularly through the atmosphere.

- **irradiation** – the measure of the energy density of sunlight
- **latitude** – the angular distance north or south from the equator
- **Ohm's Law** – the current in a circuit is directly proportional to the voltage across the circuit, and inversely proportional to the total resistance of the circuit

  $$\mathbf{I = V / R}$$
  $$\mathbf{V = I \times R}$$
  $$\mathbf{R = V / I}$$

  By substituting the equation for power (**P = V x I**), variations in Ohm's law can also be expressed as follows:

  $$\mathbf{P = I^2 \times R}$$
  $$\mathbf{P = V^2/R}$$
- **peak sun hours** – the equivalent number of hours at peak sun conditions ($1kW/m^2$) that produces the same total insolation as actual Sun conditions
- **solar incidence** – the angle that the Sun's rays strike the earth in relation to surface normal at a given longitude and latitude

Related Reading

- ***Photovoltaics: Design and Installation Manual*** by Solar Energy International (New Society Publishers, 2004)
  Solar Energy International (SEI) is a non-profit that trains adults and youth in renewable energy and environmental building technologies. This manual is well-suited for those who have some electrical experience, and students in high school tech prep-level courses. The book contains an overview of photovoltaic electricity and a detailed description of PV system components, including PV modules, batteries, controllers and inverters. It also includes chapters on sizing photovoltaic systems, analyzing sites and installing PV systems.

Internet Sites:

https://www.fsec.ucf.edu/go/solar_basics/

Florida Solar Energy Center's photovoltaic fundamentals page explains the basics of photovoltaic cells including their manufacture, the components of systems, as well as the pros and cons of photovoltaic power.

http://www.ncdc.noaa.gov/data-access/land-based-station-data/land-based-datasets/solar-radiation/

National Oceanic and Atmospheric Administration's (NOAA) National Climatic Data Center is responsible for preserving, monitoring, assessing, and providing public access to the Nation's treasure of climate and historical weather data and information. Here you can find data on solar radiation and climate conditions in the United States.

https://pvwatts.nrel.gov/

National Renewable Energy Lab's PVWatts calculator, lets you enter an address and system parameters, and it shows electrical output. The calculator lets you manipulate the inputs to see how the output changes

http://rredc.nrel.gov/solar/old_data/nsrdb/

National Solar Radiation Database contains 30 years (1961-1990) of solar radiation and supplementary meteorological data from 237 NWS sites, plus a user manual to help in reading the tabular information.

http://wrdc-mgo.nrel.gov/

World Radiation Data Centre. Worldwide solar radiation site.

Photovoltaic Orientation & Power Output

Florida NGSS Standards & Related Subject Common Core

		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
Nature of Science																					
Standard 1	**SC.912.N.1.**				X	X															
Earth and Space																					
Standard 5	**SC.912.E.5.**											X									
Standard 7	**SC.912.E.7**				X			X													
Physical Science																					
Standard 10	**SC.912.P.10.**	X	X													X				X	
Mathematics Standards		MAFS.912.N-Q.1.1, MAFS.912.N-Q.1.2, MAFS.912.N-Q.1.3, MAFS.912.A.CED.1.2, MAFS.912.A-REI.1.2, MAFS.912.S-ID.1.1, MAFS.912.S-ID.1.3, MAFS.K12.MP.1.1, MAFS.K12.MP.4.1																			

Science–Standard 1: The Practice of Science
- SC.912.N.1.4 - Identify sources of information and assess their reliability according to the strict standards of scientific investigation.
- SC.912.N.1.5 - Describe and provide examples of how similar investigations conducted in many parts of the world result in the same outcome.

Science–Standard 5: Earth in Space and Time
- SC.912.E.5.11 - Distinguish the various methods of measuring astronomical distances and apply each in appropriate situations.

Science–Standard 7: Earth System Patterns
- SC.912.E.7.4 - Summarize the conditions that contribute to the climate of a geographic area, including: atmosphere, hydrosphere, cryosphere, geosphere, and biosphere.
- SC.912.E.7.7 - Identify, analyze, and relate the internal (Earth system) and external (astronomical) conditions that contribute to global climate change.

Science–Standard 10: Energy
- SC.912.P.10.1 - Differentiate among the various forms of energy and recognize that they can be transformed from one form to others.
- SC.912.P.10.2 - Explore the Law of Conservation of Energy by differentiating among open, closed, and isolated systems and explain that the total energy in an isolated system is a conserved quantity.
- SC.912.P.10.15 - Investigate and explain the relationship among current, voltage,

resistance, and power.

- SC.912.P.10.19 - Explain that all objects emit and absorb electromagnetic radiation and distinguish between objects that are black body radiators and those that are not.

Mathematics–Number & Quantity

- MAFS.912.N-Q.1.1 - Use units as a way to understand problems and to guide the solution of multi-step problems; choose and interpret units consistently in formulas.
- MAFS.912.N-Q.1.2 - Define appropriate quantities for the purpose of descriptive modeling.
- MAFS.912.N-Q.1.3 - Choose a level of accuracy appropriate to limitations on measurement when reporting quantities.

Mathematics–Algebra

- MAFS.912.A.CED.1.2 - Create equations in two or more variables to represent relationships between quantities.
- MAFS.912.A-REI.1.2 - Solve simple rational and radical equations in one variable, and give examples showing how extraneous solutions may arise.

Mathematics–Statistics & Probability

- MAFS.9121.S-ID.1.1 - Represent data with plots on the real number line.
- MAFS.912.S-ID.1.3 - Interpret differences in shape, center, and spread in the context of the data sets, accounting for possible effects of extreme data points.

Mathematics–Mathematical Practice

- MAFS.K12.MP.1.1 - Make sense of problems and persevere in solving them.
- MAFS.K12.MP.4.1 - Model with mathematics.

National Next Generation Science Standards

Energy

- HS-PS3-1 - Create a computational model to calculate the change in the energy of one component in a system when the change in energy of the other components and energy flows in and out of the system are known.

Earth and Human Activity

- HS-ESS3-2 - Evaluate competing design solutions for developing, managing, and utilizing energy and mineral resources based on cost-benefit ratios.
- HS-ESS3-4 - Evaluate or refine a technological solution that reduces impacts of human activities on natural systems.

Note: Related Common Core Mathematics Standards are listed in the Florida section above.

Photovoltaic Orientation & Power Output

You might have inferred from Activity 1, that the direction a photovoltaic module is facing in respect to the position of the sun affects its power output. In this activity you are going to investigate some of the orientation factors that affect the electrical output of the PV device.

Solar Irradiance
Use an insolation meter to measure the amount of solar irradiance (kW/m^2). Make sure you face the meter directly at the Sun. Record below the highest reading that you obtain and complete the information below.

Date ________________ Time ___________ Daylight Savings Time? ___ yes ___ no

Latitude _______________________________ Irradiance reading ________________ W/m^2

Solar Incidence

1. Calculate the solar incidence. To do this, take a long slender object (such as a rod or pencil) and with one end touching the ground, point the other end towards the Sun. When you are pointing directly at the Sun, the pointer will not cast any shadow. Use a protractor to measure the angle between the rod and the ground and record it below.

   Angle of solar incidence ________________

Array Tilt Angle

2. Does a module's angle in relation to the Sun have an affect on its output power? Use your protractor to set the array tilt angle (the angle that the module is tilting up from the ground) for each of the angles listed in the data chart below. Measure and record the voltage and current for each of the array tilt angles listed in the data table. Repeat the test three times to verify your angle measurements. Calculate the averages of the current and voltage readings for each angle. Calculate the power output.
   (Remember: $P = V \times I$).

   Note: Irradiation readings should be as constant as possible throughout the whole investigation. If the weather is not perfectly clear, have one team member watch the readings on the irradiance meter and advise if there is a significant change (+/- 50 kW/m^2) due to cloud cover. During the test, readings should be taken quickly to minimize the effect of a change in irradiance level.

Module Tilt Angle	Voltage				Current				Power Output
	Trial 1	Trial 2	Trial 3	Average	Trial 1	Trial 2	Trial 3	Average	
0º									
10º									
20º									
30º									
40º									
50º									
60º									
70º									
80º									
90º									
Irradiance									X

Application and Analysis

3. Graph (on a separate sheet) the change of power output as a function of the changing tilt angle. Your title should include the average irradiance level and your axis should be labeled properly. (Note: Your independent variable–what you manipulated–goes on the x-axis)

4. What is the affect of the tilt angle on the PV system's voltage and current?

5. At what tilt angle did the module produce the most power?

6. What is the relationship between the angle that produced the most power and the angle of incidence? (Hint: Think geometrically. Draw a diagram if necessary)

7. Write a formula below that you could use to determine the optimum array tilt angle given a specific angle of solar incidence. Use β for the array tilt angle and α for the sun's angle of incidence.

8. Explain how this optimum tilt angle is related to the time of day, season and latitude of the location.

Solar Azimuth

9. Azimuth is the horizontal measurement of the compass angle that the Sun is away from due south* (solar noon) as it appears to travel across the sky during the day. To determine this angle, draw a straight line about 8 inches long on a sheet of paper. With a compass, orient the paper so that the line is running from north to south, and anchor the paper securely with tape. Place a long rod (or a pencil) with one end on the north/south line, positioning it straight up vertically (90º). Using a protractor, measure the angle between your north/south line and the shadow that the rod is casting. This is the current azimuth angle of the Sun. Azimuth angles when the sun is on the east side of solar noon are considered positive angles; towards the west side have negative angles. Record the azimuth angle and other information below.

Date ________________ Time ____________ Daylight Savings Time? ___ yes ___ no

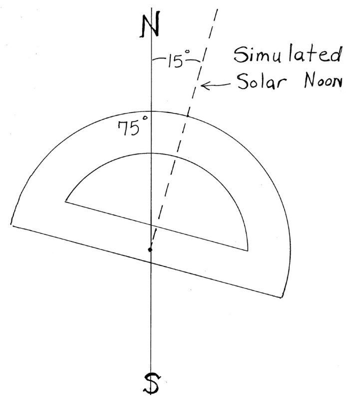
Latitude _________________________________ Azimuth angle _________________________

* Note: In the southern hemisphere, due north used for solar noon.

10. In one hour approximately how many degrees azimuth will the Sun appear to travel?

11. How does the change in the azimuth angle during the day affect the power output of your PV module? One way to determine this would be to take measurements throughout the day as the Sun changed its angle in relation to your panel; but another way, and easier to do during class time, is to roughly simulate the same effect by rotating the module in relation to the Sun.
    - Set your panel at the optimal tilt angle from the previous activity, and keep this measurement constant throughout this investigation. An easy way to do this is to make an angle "template" by folding and taping a strip of heavy paper into a triangle in which the face of the isosceles triangle is the correct angle. (Hint: Hold the panel at the optimal tilt angle and fold and tape the paper to match it.) This template can then be used to "set" each tilt angle during the investigation.
    - Use your north/south lined paper from the exercise above and a protractor to set your module at the azimuth angles in the data table below. The diagram below

shows an easy way to make sure that your module is at the correct azimuth angle. Your panel would be set in line with the straight edge of the protractor, and the protractor rotated right and left to the simulated azimuth angles. The diagram below illustrates the protractor setting for a simulated azimuth angle of -75º.



Measure and record the voltage and the amperage for each of the simulated azimuth angles in the data table below. Use the current azimuth angle as a simulated "solar noon" then plus (east side) or minus (west side) the given angles.

- Repeat the test three times to justify your measure and calculate the average current and voltage readings for each angle. Use these average values to calculate the power.

Note: Irradiation readings should be as constant as possible throughout this investigation. If the weather is not perfectly clear, have one team member watch the readings on the isolation meter and advise if there is a significant change (+/- 50 kW/m^2). All readings should be taken quickly to minimize the effect of a change in irradiance level.

Simulated Azimuth Angles		**Voltage**				**Amperage**				**Power Output**
		Trial 1	**Trial 2**	**Trial 3**	**Average**	**Trial 1**	**Trial 2**	**Trail 3**	**Average**	
Simulated a.m.	**+90º**									
	+75º									
	+60º									
	+45º									
	+30º									
	+15º									
Azimuth (simulated solar noon)										

Simulated p.m.	-15º									
	-30º									
	-45º									
	-60º									
	-75º									
	-90º									
Irradiance										X

Application and Analysis

12. Is there a pattern between the simulated azimuth angles and power calculations?

13. On a separate sheet, graph the change of power output (dependant variable) as a function of the changing solar azimuth. Include the average irradiance level and indicate that this is an azimuth "simulation"in your title. Label the x-axis with the time that the angle values represent. (Hint: use your answer from question 10 to help you.)

14. Which direction should a fixed solar panel face so that it produces the most energy?

15. Based on your simulation data, during what time(s) of the day would you expect to see the greatest power output from your module?

16. Based on your simulation data, between what hours of the day would you expect to see a power output of at least 50% of the module's potential?

17. Explain the changes in the total energy being produced by the solar module.

18. Some photovoltaic devices are positioned to produce their maximum power output during the utilities" peak load times. Assume that the peak load time for the electric utility in your area is 4:00 - 6:00 pm, and you want to maximize the power output of your array for this time range. Predict the direction that you would request installation of your array.

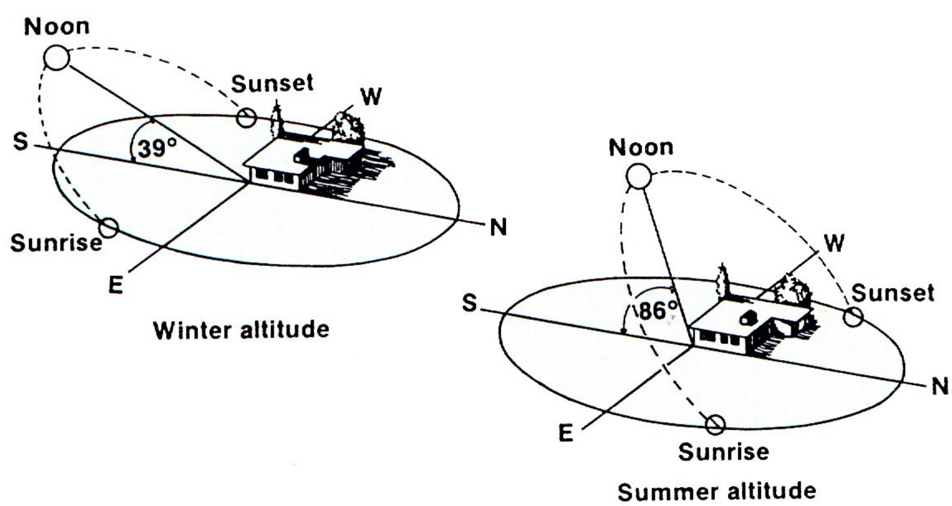
19. What factor did our simulation fail to take into account for times of day when the Sun is lower on the horizon? (Hint: consider the affects of the atmosphere) How would you expect this to affect the power outputs that you observed?

20. Would you expect more or less energy to be available if the panel were able to “track” the Sun’s path throughout the day?

21. What are some of the factors that would have to be taken into account when making a decision on whether to use a fixed or a tracking panel? Compare both energy output and economic factors.

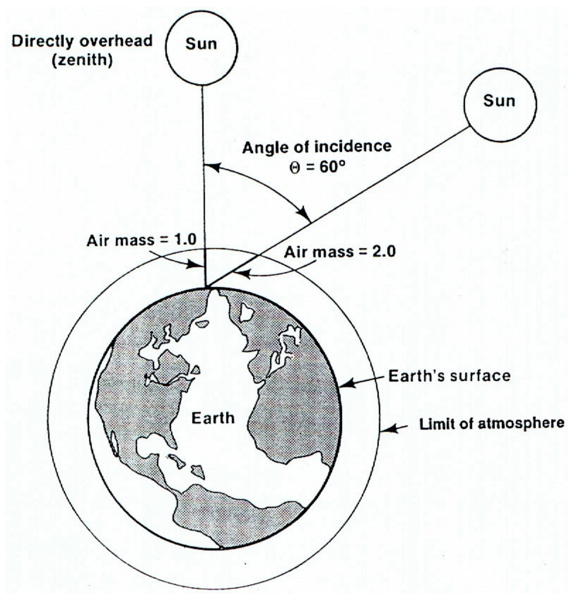
Seasonal Changes

As you are probably aware, the sun’s path through the sky varies with the seasons. The diagram below illustrates the seasonal paths of the sun at 28° north latitude.



Sun paths for 28° N. latitude

As you can see, the solar incidence changes with the seasons at this latitude by as much as 45°, which would therefore impact the optimal array tilt angle. Additionally, when the Sun is lower on the horizon (lower angle of incidence) either because of the season or time of day, the solar radiation must travel through more of the atmosphere before it strikes the earth. The increased amount of atmosphere that must be passed through decreases the amount of solar irradiance because more of the solar energy is reflected, absorbed, refracted and scattered before it reaches the ground.



Insolation Data

Many sites and labs have been collecting irradiance data since the 1960s. Data tables are available and used in photovoltaic system design and installation. The raw irradiation data collected is used to calculate *insolation*, or *Peak Sun Hours*, which is the number of hours at 1kW/m^2 that the actual total sun conditions equal. Therefore, with this standard it is possible to compare the amount of sunlight between locations anywhere on the planet, or design an efficient photovoltaic system for a location without having to personally collect extensive insolation measurements. Below is data collected from Orlando, FL (latitude 28.55)

Insolation – kWh/m^2-day for Orlando, FL

Tilt	Jan	Feb	Mar	Apr	Ma	Jun	July	Aug	Sept	Oct	Nov	Dec	Annual
0°	3.14	3.92	4.99	5.99	6.27	5.78	5.68	5.28	4.72	4.11	3.46	2.92	4.69
15°	3.75	4.43	5.30	6.05	6.10	5.54	5.49	5.24	4.89	4.53	4.06	3.56	4.91
20°	3.92	4.56	5.36	6.01	5.99	5.41	5.37	5.18	4.90	4.63	4.23	3.74	4.94
25°	4.07	4.67	5.39	5.95	5.85	5.26	5.23	5.10	4.89	4.70	4.37	3.90	4.95
30°	4.19	4.75	5.39	5.85	5.67	5.07	5.06	4.99	4.86	4.75	4.49	4.04	4.93
35°	4.29	4.80	5.36	5.72	5.47	4.87	4.87	4.85	4.79	4.77	4.58	4.15	4.88
40°	4.37	4.82	5.31	5.56	5.24	4.63	4.66	4.69	4.71	4.76	4.64	4.24	4.80

22. Using the information above, what is the annual horizontal solar insolation (in kWh/m^2-day) for Orlando, FL?

23. Determine the maximum annual insolation that was recorded in Orlando. What month and what tilt angle was this value recorded at?

24. Determine the worst month of the year for collecting solar insolation in Orlando. For that particular month, what tilt angle should be used to collect the maximum amount of solar energy?

25. Would you expect the insolation data collected for this year to be *exactly* the same, approximately the same, or completely different than the data in the table above? Why?

Summary

When installing or positioning a solar module, it is critical to consider many factors related to the system's location, the Sun's position and the Sun's path through the sky. Because of the Earth's daily rotation on its axis and the Earth's revolution around the Sun, the solar radiation striking the surface of a solar module continuously changes. The intensity of solar irradiance and the angle at which this radiation hits the PV panel determines the amount of electricity it generates. To optimize the *annual* energy output, most installations are mounted at 90% of local latitude. For applications that are designed for a *winter peak load* the best array tilt angle is latitude plus 15^{o}, and for a *summer peak load* the best array tilt angle is latitude minus 15^{o}.

Photovoltaic Orientation & Power Output

1. Given an angle of incidence of 75°, what is the optimum array tilt angle at that specific moment?

2. At 1:00 pm the solar azimuth is -22°, what will the azimuth be at 4:00 pm?

Using the data sheets below, compare the solar insolation for the three cities: Orlando FL, Tonopah NV, and Spokane WA. to answer questions 3 - 7.

Solar Radiation for Collectors Facing South At A Fixed Tilt

Insolation – kWh/m²-day – for Orlando, FL (28.55° North Latitude)

Tilt	Jan	Feb	Mar	Apr	Ma	Jun	July	Aug	Sept	Oct	Nov	Dec	Annual
0°	3.14	3.92	4.99	5.99	6.27	5.78	5.68	5.28	4.72	4.11	3.46	2.92	4.69
15°	3.75	4.43	5.30	6.05	6.10	5.54	5.49	5.24	4.89	4.53	4.06	3.56	4.91
20°	3.92	4.56	5.36	6.01	5.99	5.41	5.37	5.18	4.90	4.63	4.23	3.74	4.94
25°	4.07	4.67	5.39	5.95	5.85	5.26	5.23	5.10	4.89	4.70	4.37	3.90	4.95
30°	4.19	4.75	5.39	5.85	5.67	5.07	5.06	4.99	4.86	4.75	4.49	4.04	4.93
35°	4.29	4.80	5.36	5.72	5.47	4.87	4.87	4.85	4.79	4.77	4.58	4.15	4.88
40°	4.37	4.82	5.31	5.56	5.24	4.63	4.66	4.69	4.71	4.76	4.64	4.24	4.80

Insolation – kWh/m²-day – for Tonopah, NV (38.07° North Latitude)

Tilt	Jan	Feb	Mar	Apr	Ma	Jun	July	Aug	Sept	Oct	Nov	Dec	Annual
0°	2.90	4.02	5.61	7.10	8.13	8.80	8.53	7.69	6.44	4.80	3.25	3.61	5.82
25°	4.40	5.38	6.56	7.45	7.91	8.28	8.15	7.81	7.21	6.12	4.75	4.17	6.52
30°	4.63	5.57	6.65	7.41	7.73	8.04	7.94	7.71	7.25	6.29	4.97	4.41	6.55
35°	4.83	5.72	6.69	7.31	7.52	7.76	7.69	7.57	7.24	6.42	5.16	4.63	6.55
40°	5.00	5.84	6.70	7.18	7.27	7.44	7.40	7.38	7.19	6.50	5.31	4.81	6.51
45°	5.14	5.92	6.67	7.01	6.98	7.08	7.07	7.16	7.10	6.55	5.44	4.96	6.43
50°	5.24	5.96	6.60	6.80	6.65	6.70	6.71	6.89	6.97	6.56	5.52	5.08	6.31

Insolation – kWh/m²-day – for Spokane, WA (47.63° North Latitude)

Tilt	Jan	Feb	Mar	Apr	Ma	Jun	July	Aug	Sept	Oct	Nov	Dec	Annual
0°	0.99	1.91	3.28	4.72	6.05	6.57	7.44	6.13	4.53	2.65	1.25	0.81	3.86
35°	1.84	2.93	4.13	5.10	5.91	6.14	7.12	6.41	5.45	3.84	2.18	1.63	4.40
40°	1.92	3.01	4.16	5.04	5.76	5.95	6.92	6.31	5.46	3.93	2.27	1.71	4.38
45°	1.99	3.08	4.17	4.97	5.59	5.73	6.69	6.18	5.44	3.99	2.34	1.78	4.34
50°	2.05	3.13	4.16	4.86	5.39	5.49	6.42	6.01	5.39	4.03	2.40	1.84	4.27
55°	2.09	3.15	4.12	4.73	5.17	5.22	6.13	5.81	5.31	4.05	2.44	1.89	4.18
60°	2.12	3.16	4.06	4.58	4.92	4.93	5.80	5.59	5.20	4.04	2.46	1.92	4.07

3. What is the annual horizontal solar insolation (in kWhr) for each of the three cities?

4. What is the maximum annual insolation and the corresponding tilt angle for each of the three cities?

5. For what month of the year can the maximum amount of average daily solar insolation be collected for each of the three cities? What are these amounts and what are the corresponding tilt angles?

6. What is the worst month of the year for collecting solar insolation for each of the three cities? For the worst month of the year for each city, what tilt angles should be used to collect the maximum amount of solar energy?

7. Of the three cities above, does the southern-most city receive the most solar energy during the summer? during the winter? on an annual basis?

8. Why do you think this is so?

9. What are the consequences of tilting a PV array at angles
   (a) lower than the local latitude?

   (b) higher than the local latitude?

10. What are the consequences of orienting a PV array off-azimuth (solar noon)?